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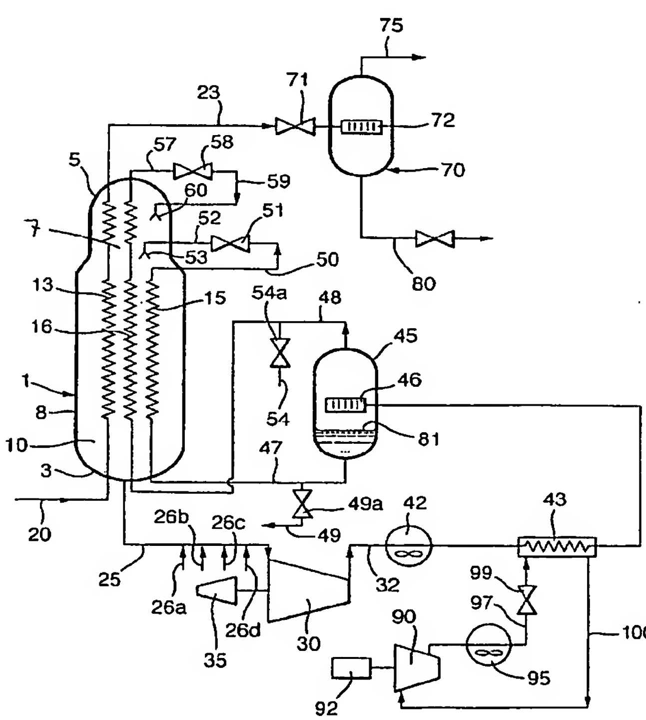
(54) Title: PROCESS OF LIQUEFYING A GASEOUS, METHHANE-RICH FEED TO OBTAIN LIQUEFIED NATURAL GAS



(57) Abstract: Cooling and liquefying a gaseous, methane-rich feed (20) in a main heat exchanger (1) against evaporating refrigerant to get a liquefied stream (23) and passing (80) the liquefied stream (23) to storage as liquefied product. The process comprises adjusting the composition and the amount of refrigerant and controlling the liquefaction process, using an advanced process controller based on model predictive control to determine simultaneous control actions for a set of manipulated variables in order to optimize at least one of a set of parameters whilst controlling at least one of a set of controlled variables, wherein the set of manipulated variables includes the mass flow rate of the heavy refrigerant fraction (52) the mass flow rate of the light refrigerant fraction (59), the amount of refrigerant components make-up (26), the amount of refrigerant removed (54), the capacity of the refrigerant compressor (30, 32) and the mass flow rate of the methane-rich feed (20) wherein the set of controlled variables includes the temperature difference at the warm end (3) of the main heat exchanger (1), a variable relating to the temperature of the liquefied natural gas (23), the composition of the refrigerant entering the separator (45), the pressure in the shell of the main heat exchanger (1), the pressure in the separator (45) and the level of the liquid in the separator (45), and wherein the set of variables to be optimized includes the production of liquefied product (80).

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— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

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PROCESS OF LIQUEFYING A GASEOUS, METHANE-RICH FEED TO OBTAIN LIQUEFIED NATURAL GAS

The present invention relates to a process of liquefying a gaseous, methane-rich feed to obtain a liquefied product. The liquefied product is commonly called liquefied natural gas. In particular the present invention relates to controlling the liquefaction process.

The liquefaction process comprises the steps of:

(a) supplying the gaseous, methane-rich feed at elevated pressure to a first tube side of a main heat exchanger at its warm end, cooling, liquefying and sub-cooling the gaseous, methane-rich feed against evaporating refrigerant to get a liquefied stream, removing the liquefied stream from the main heat exchanger at its cold end and passing the liquefied stream to storage as liquefied product;

(b) removing evaporated refrigerant from the shell side of the main heat exchanger at its warm end;

(c) compressing in at least one refrigerant compressor the evaporated refrigerant to get high-pressure refrigerant;

(d) partly condensing the high-pressure refrigerant and separating in a separator the partly-condensed refrigerant into a liquid heavy refrigerant fraction and a gaseous light refrigerant fraction;

(e) sub-cooling the heavy refrigerant fraction in a second tube side of the main heat exchanger to get a sub-cooled heavy refrigerant stream, introducing the heavy refrigerant stream at reduced pressure into the shell side of the main heat exchanger at its mid-point, and

allowing the heavy refrigerant stream to evaporate in the shell side; and

(f) cooling, liquefying and sub-cooling at least part of the light refrigerant fraction in a third tube side of the main heat exchanger to get a sub-cooled light refrigerant stream, introducing the light refrigerant stream at reduced pressure into the shell side of the main heat exchanger at its cold end, and allowing the light refrigerant stream to evaporate in the shell side.

International patent application publication No. 99/31 448 discloses controlling a liquefaction process. In the known control process, an advanced process controller based on model predictive control is used to determine simultaneous control actions for a set of manipulated variables in order to optimize at least one of a set of parameters whilst controlling at least one of a set of controlled variables, wherein the set of manipulated variables includes the mass flow rate of the heavy refrigerant fraction, the mass flow rate of the light refrigerant fraction and the mass flow rate of the methane-rich feed, wherein the set of controlled variables includes the temperature difference at the warm end of the main heat exchanger and the temperature difference at the mid-point of the main heat exchanger, and wherein the set of variables to be optimized includes the production of liquefied product.

The known process was considered to be advantageous because the bulk composition of the mixed refrigerant was not manipulated to optimize the production of liquefied product. However, Applicant had now found that separately controlling the bulk composition of the mixed refrigerant is cumbersome.

It is an object of the present invention to provide an alternative process, wherein control of the bulk composition of the mixed refrigerant is included.

To this end the process of liquefying a gaseous, methane-rich feed to obtain a liquefied product is characterized in that the process further comprises adjusting the composition and the amount of refrigerant and controlling the liquefaction process, using an advanced process controller based on model predictive control to determine simultaneous control actions for a set of manipulated variables in order to optimize at least one of a set of parameters whilst controlling at least one of a set of controlled variables, wherein the set of manipulated variables includes the mass flow rate of the heavy refrigerant fraction, the mass flow rate of the light refrigerant fraction, the amount of refrigerant components make-up, the amount of refrigerant removed, the capacity of the refrigerant compressor and the mass flow rate of the methane-rich feed, wherein the set of controlled variables includes the temperature difference at the warm end of the main heat exchanger, a variable relating to the temperature of the liquefied natural gas, the composition of the refrigerant entering the separator of step (d), the pressure in the shell of the main heat exchanger, the pressure in the separator of step (d) and the level of the liquid in the separator of step (d), and wherein the set of variables to be optimized includes the production of liquefied product.

In the specification and in the claims the term 'manipulated variable' is used to refer to variables that can be manipulated by the advanced process controller, and the term 'controlled variables' is used to refer to variables that have to be kept by the advanced process controller at a predetermined value (set point) or within a predetermined range (set range). The expression 'optimizing a variable' is used to refer to maximizing or minimizing the variable and to maintaining the variable at a predetermined value.

Model predictive control or model based predictive control is a well-known technique, see for example Perry's Chemical Engineers' Handbook, 7th Edition, pages 8-25 to 8-27. A key feature of model predictive control is that future process behaviour is predicted using a model and available measurements of the controlled variables. The controller outputs are calculated so as to optimize a performance index, which is a linear or quadratic function of the predicted errors and calculated future control moves. At each sampling instant, the control calculations are repeated and the predictions updated based on current measurements. A suitable model is one that comprises a set of empirical step-response models expressing the effects of a step-response of a manipulated variable on the controlled variables.

An optimum value for the parameter to be optimized can be obtained from a separate optimization step, or the variable to be optimized can be included in the performance function.

Before model predictive control can be applied, one determines first the effect of step changes of the manipulated variables on the variable to be optimized and on the controlled variables. This results in a set of step-response coefficients. This set of step-response coefficients forms the basis of the model predictive control of the liquefaction process.

During normal operation, the predicted values of the controlled variables are regularly calculated for a number of future control moves. For these future control moves a performance index is calculated. The performance index includes two terms, a first term representing the sum over the future control moves of the predicted error for each control move and a second term representing the sum over the future control moves of the change in the

manipulated variables for each control move. For each controlled variable, the predicted error is the difference between the predicted value of the controlled variable and a reference value of the controlled variable. The predicted errors are multiplied with a weighting factor, and the changes in the manipulated variables for a control move are multiplied with a move suppression factor. The performance index discussed here is linear.

Alternatively, the terms may be a sum of squared terms, in which case the performance index is quadratic.

Moreover, constraints can be set on manipulated variables, change in manipulated variables and on controlled variables. This results in a separate set of equations that are solved simultaneously with the minimization of the performance index.

Optimization can be done in two ways; one way is to optimize separately, outside the minimization of the performance index, and the second way is to optimize within the performance index.

When optimization is done separately, the variables to be optimized are included as controlled variables in the predicted error for each control move and the optimization gives a reference value for the controlled variables.

Alternatively, optimization is done within the calculation of the performance index, and this gives a third term in the performance index with an appropriate weighting factor. In this case, the reference values of the controlled variables are pre-determined steady state values, which remain constant.

The performance index is minimized taking into account the constraints to give the values of the manipulated variables for the future control moves. However, only the next control move is executed. Then the

calculation of the performance index for future control moves starts again.

The models with the step response coefficients and the equations required in model predictive control are part of a computer program that is executed in order to control the liquefaction process. A computer program loaded with such a program that can handle model predictive control is called an advanced process controller. Because the computer programs are commercially available, we will not discuss such programs in detail. The present invention is more directed to selecting the variables.

The invention will now be described by way of example with reference to the accompanying drawing showing schematically a flow scheme of a plant for liquefying natural gas.

The plant for liquefying natural gas comprises a main heat exchanger 1 with a warm end 3, a cold end 5 and a mid-point 7. The wall 8 of the main heat exchanger 1 defines a shell side 10. In the shell side 10 are located a first tube side 13 extending from the warm end 3 to the cold end 5, a second tube side 15 extending from the warm end 3 to the mid-point 7 and a third tube side 16 extending from the warm end 3 to the cold end 5.

During normal operation, a gaseous, methane-rich feed is supplied at elevated pressure through supply conduit 20 to the first tube side 13 of the main heat exchanger 1 at its warm end 3. The feed, which passes through the first tube side 13, is cooled, liquefied and sub-cooled against refrigerant evaporating in the shell side 10. The resulting liquefied stream is removed from the main heat exchanger 1 at its cold end 5 through conduit 23. The liquefied stream is passed to storage (not shown) where it is stored as liquefied product at atmospheric pressure.

Evaporated refrigerant is removed from the shell side 10 of the main heat exchanger 1 at its warm end 3 through conduit 25. To adjust the bulk composition of the refrigerant, components, such as nitrogen, methane, ethane and propane can be added to the refrigerant in conduit 25 through conduits 26a, 26b, 26c and 26d. The conduits 26a through d are provided with suitable valves (not shown) controlling the flow of the components into the conduit 25. The refrigerant is also called mixed refrigerant or multicomponent refrigerant.

In a refrigerant compressor 30, the evaporated refrigerant is compressed to get high-pressure refrigerant that is removed through conduit 32. The refrigerant compressor 30 is driven by a suitable motor, for example a gas turbine 35, which is provided with a starter-helper motor (not shown).

Refrigerant at high pressure in conduit 32 is cooled in air cooler 42 and partly condensed in heat exchanger 43 to obtain partly-condensed refrigerant. The air cooler 42 can be replaced by a heat exchanger in which refrigerant is cooled against seawater.

The high-pressure refrigerant is introduced into a separator in the form of separator vessel 45 through inlet device 46. In the separator vessel 45, the partly-condensed refrigerant is separated into a liquid heavy refrigerant fraction and a gaseous light refrigerant fraction. The liquid heavy refrigerant fraction is removed from the bottom of the separator vessel 45 through conduit 47, and the gaseous light refrigerant fraction is removed through conduit 48.

To adjust the amount of refrigerant, heavy refrigerant can be drained through conduit 49 provided with valve 49a.

The heavy refrigerant fraction is sub-cooled in the second tube side 15 of the main heat exchanger 1 to get a

sub-cooled heavy refrigerant stream. The sub-cooled heavy refrigerant stream is removed from the main heat exchanger 1 through conduit 50, and allowed to expand over an expansion device in the form of an expansion valve 51. At reduced pressure it is introduced through conduit 52 and nozzle 53 into the shell side 10 of the main heat exchanger 1 at its mid-point 7. The heavy refrigerant stream is allowed to evaporate in the shell side 10 at reduced pressure, thereby cooling the fluids in the tube sides 13, 15 and 16.

To adjust the amount of refrigerant, gaseous light refrigerant can be vented through conduit 54 provided with valve 54a.

The gaseous light refrigerant fraction removed through conduit 48 is passed to the third tube side 16 in the main heat exchanger 1 where it is cooled, liquefied and sub-cooled to get a sub-cooled light refrigerant stream. The sub-cooled light refrigerant stream is removed from the main heat exchanger 1 through conduit 57, and allowed to expand over an expansion device in the form of an expansion valve 58. At reduced pressure it is introduced through conduit 59 and nozzle 60 into the shell side 10 of the main heat exchanger 1 at its cold end 5. The light refrigerant stream is allowed to evaporate in the shell side 10 at reduced pressure, thereby cooling the fluids in the tube sides 13, 15 and 16.

The resulting liquefied stream is removed from the main heat exchanger 1 through the conduit 23 and passed to flash vessel 70. The conduit 23 is provided with an expansion device in the form of an expansion valve 71 in order to allow reduction of the pressure, so that the resulting liquefied stream is introduced via inlet device 72 in the flash vessel 70 at a reduced pressure. The reduced pressure is suitably substantially equal to

atmospheric pressure. Expansion valve 71 also regulates the total flow.

From the top of the flash vessel 70 an off-gas is removed through conduit 75. The off-gas can be compressed in an end-flash compressor (not shown) to get high-pressure fuel gas.

From the bottom of the flash vessel 70 liquefied product is removed through conduit 80 and passed to storage (not shown).

A first objective is to maximize production of liquefied product flowing through conduit 80, which is manipulated by expansion valve 71.

To achieve this objective the liquefaction process is controlled using an advanced process controller based on model predictive control to determine simultaneous control actions for a set of manipulated variables in order to optimize the production of liquefied product whilst controlling at least one of a set of controlled variables.

The set of manipulated variables includes the mass flow rate of the heavy refrigerant fraction flowing through conduit 52 (expansion valve 51), the mass flow rate of the light refrigerant fraction flowing through conduit 57 (expansion valve 58), the amount of refrigerant components make-up (supplied through conduits 26a through d), the amount of refrigerant removed by bleeding through conduit 49 and/or venting through conduit 54, the capacity of the refrigerant compressor 30 and the mass flow rate of the methane-rich feed through conduit 20 (which is manipulated by expansion valve 71). In an alternative embodiment an expansion turbine (not shown) can be arranged in conduit 23, upstream of the expansion valve 71.

Of these manipulated variables, the mass flow rate of the heavy refrigerant fraction, the mass flow rate of the

light refrigerant fraction, the amount of refrigerant components make-up, and the amount of refrigerant removed by bleeding and/or venting are manipulated variables that relate to the inventory or amount of the mixed refrigerant.

The capacity of the refrigerant compressor 30 (or compressors if more than one refrigerant compressor is used) is determined by the speed of the refrigerant compressor, the angle of the inlet guide vane of the refrigerant compressor, or both the speed of the refrigerant compressor and the angle of the inlet guide vane. Thus, the manipulated variable capacity of the refrigerant compressor is the speed of the refrigerant compressor, the angle of the inlet guide vane of the refrigerant compressor, or both the speed of the refrigerant compressor and the angle of the inlet guide vane.

The set of controlled variables includes the temperature difference at the warm end 3 of the main heat exchanger 1 (which is the difference between the temperature of the fluid in conduit 20 and the temperature in conduit 25).

Suitably an additional variable is controlled, which is the temperature difference at the mid point 7, which is the difference between the temperature of the gas being liquefied in the first tube side 13 at the midpoint 7 and the temperature of the fluid in the shell side 10 of the main heat exchanger 1 at the mid point 7. In the specification and the claims, this temperature difference will be referred to as the first mid point temperature difference.

Suitably an additional variable is controlled, which is the temperature difference at the mid point 7, which is the difference between the temperature of the gas being liquefied in the first tube side 13 at the

midpoint 7 and the temperature of the heavy mixed refrigerant stream introduced through conduit 52. In the specification and the claims, this temperature difference will be referred to as the second mid point temperature difference.

Suitably a further controlled variable is the temperature of the gas being liquefied in the first tube side 13 at the midpoint 7.

The set of controlled variables also includes a variable relating to the temperature of the liquefied natural gas. Moreover the set of controlled variables includes the composition of the refrigerant entering the separator vessel 45, the pressure in the shell 10 of the main heat exchanger 1, the pressure in the separator vessel 45, and the level 81 of the liquid in the separator vessel 45.

The set of variables to be optimized includes the production of liquefied product.

By selecting these variables, control of the main heat exchanger 1 with advanced process control based on model predictive control is achieved.

Applicant had found that thus an efficient and rapid control can be achieved that allows optimizing the production of liquefied product, controlling the temperature profile in the main heat exchanger and controlling the refrigerant composition and amount or inventory of the refrigerant.

Essential for the present invention is the insight that the composition and the inventory of the mixed refrigerant cannot be separated from optimizing the production of liquefied product.

One of the controlled variables is the temperature difference at the warm end 3 of the main heat exchanger 1, which is the difference between the temperature of the fluid in conduit 20 and the

temperature in conduit 25. The temperature of the warm end 3 is kept between predetermined limits (a minimum limit value and a limit maximum value) in order to ensure that no liquid refrigerant is withdrawn from the shell side 10 through conduit 25.

Suitably an additional variable is controlled, which is the temperature difference at the mid point 7, which is the difference between the temperature of the gas being liquefied in the first tube side 13 at the midpoint 7 and the temperature of the fluid in the shell side 10 of the main heat exchanger 1 at the mid point 7. This first mid point temperature difference should remain in a predetermined range.

Suitably an additional variable is controlled, which is the temperature difference at the mid point 7, which is the difference between the temperature of the gas being liquefied in the first tube side 13 at the midpoint 7 and the temperature of the heavy mixed refrigerant stream introduced through conduit 53. This second mid point temperature difference should remain in a predetermined range.

Suitably a further controlled variable is the temperature of the gas being liquefied in the first tube side 13 at the midpoint 7, and this temperature should be kept below a predetermined value.

One of the controlled variables is the variable relating to the temperature of the liquefied natural gas. Suitably, this is the temperature of the liquefied natural gas removed from the main heat exchanger 1 through conduit 23. Alternatively the variable relating to the temperature of the liquefied natural gas is the amount of off-gas flowing through conduit 75.

Suitably, the set of variables to be optimized includes, in addition to the production of liquefied product, the nitrogen content of the refrigerant and the

propane content of the refrigerant, wherein the nitrogen content is minimized and the propane content is maximized.

As stated in the introduction, optimization can be done separately or it can be done in the calculation of the performance index. In the latter case, the variables to be optimized are weighted with a predetermined weighting factor. Both methods allow the operator to select to maximize the production or to optimize the refrigerant composition.

A further objective of the present invention is to maximize the utilization of the compressors. To this end the production of liquefied natural gas is maximized until a compressor constraint is reached. Therefore the set of controlled variables further includes the power required to drive the refrigerant compressor 30, or refrigerant compressors if more than one refrigerant compressor is used.

Additionally, the speed of the refrigerant compressor(s) is a controlled variable, in that it can be reduced until the maximum value of the temperature difference at the warm end 3 reaches the maximum limit value.

In heat exchanger 43 high pressure refrigerant is partly condensed. In this heat exchanger, and some others (not shown), heat is removed by means of indirect heat exchange with an auxiliary refrigerant (for example propane) evaporating at a suitable pressure in the shell side of the heat exchanger(s).

Evaporated auxiliary refrigerant is compressed in an auxiliary compressor 90 driven by a suitable motor, such as a gas turbine 92. Auxiliary refrigerant is condensed in air cooler 95, wherein air is the external coolant. Condensed auxiliary refrigerant at elevated pressure is passed through conduit 97 provided with expansion

valve 99 to the shell side of heat exchanger 43. The condensed auxiliary refrigerant is allowed to evaporate at low pressure and evaporated auxiliary refrigerant is returned through conduit 100 to the auxiliary compressor 92. It will be understood that more than one auxiliary compressor can be employed, arranged in parallel or in series.

The air cooler 95 can be replaced by a heat exchanger in which refrigerant is cooled against seawater.

In order to integrate the control of the cycle of the auxiliary refrigerant with the control of the main heat exchanger 1, the set of manipulated variables further includes the capacity of the auxiliary refrigerant compressor 90 or compressors, and the set of controlled variables further includes the power to drive the auxiliary refrigerant compressor 90 or compressors. In this way the utilization of the propane compressor can be maximized.

The capacity of the auxiliary refrigerant compressor 90 (or compressors if more than one auxiliary refrigerant compressor is used) is determined by the speed of the auxiliary refrigerant compressor, the angle of the inlet guide vane of the auxiliary refrigerant compressor, or both the speed of the refrigerant compressor and the angle of the inlet guide vane. Thus, the manipulated variable capacity of the auxiliary refrigerant compressor is the speed of the auxiliary refrigerant compressor, the angle of the inlet guide vane of the auxiliary refrigerant compressor, or both the speed of the refrigerant compressor and the angle of the inlet guide vane.

In the embodiment shown in the Figure, heavy refrigerant can be drained through conduit 49 provided with valve 49a, and gaseous light refrigerant can be vented through conduit 54 provided with valve 54a.

Alternatively, mixed refrigerant can be removed from conduit 32, downstream of the refrigerant compressor 30. In this way the amount of refrigerant can be adjusted as well.

CLAIMS

1. Process of liquefying a gaseous, methane-rich feed to obtain a liquefied product, which liquefaction process comprises the steps of:

(a) supplying the gaseous, methane-rich feed at elevated pressure to a first tube side of a main heat exchanger at its warm end, cooling, liquefying and sub-cooling the gaseous, methane-rich feed against evaporating refrigerant to get a liquefied stream, removing the liquefied stream from the main heat exchanger at its cold end and passing the liquefied stream to storage as liquefied product;

(b) removing evaporated refrigerant from the shell side of the main heat exchanger at its warm end;

(c) compressing in at least one refrigerant compressor the evaporated refrigerant to get high-pressure refrigerant;

(d) partly condensing the high-pressure refrigerant and separating in a separator the partly-condensed refrigerant into a liquid heavy refrigerant fraction and a gaseous light refrigerant fraction;

(e) sub-cooling the heavy refrigerant fraction in a second tube side of the main heat exchanger to get a sub-cooled heavy refrigerant stream, introducing the heavy refrigerant stream at reduced pressure into the shell side of the main heat exchanger at its mid-point, and allowing the heavy refrigerant stream to evaporate in the shell side; and

(f) cooling, liquefying and sub-cooling at least part of the light refrigerant fraction in a third tube side of the main heat exchanger to get a sub-cooled light refrigerant stream, introducing the light refrigerant

stream at reduced pressure into the shell side of the main heat exchanger at its cold end, and allowing the light refrigerant stream to evaporate in the shell side, characterized in that the process further comprises adjusting the composition and the amount of refrigerant and controlling the liquefaction process, using an advanced process controller based on model predictive control to determine simultaneous control actions for a set of manipulated variables in order to optimize at least one of a set of parameters whilst controlling at least one of a set of controlled variables, wherein the set of manipulated variables includes the mass flow rate of the heavy refrigerant fraction, the mass flow rate of the light refrigerant fraction, the amount of refrigerant components make-up, the amount of refrigerant removed, the capacity of the refrigerant compressor and the mass flow rate of the methane-rich feed, wherein the set of controlled variables includes the temperature difference at the warm end of the main heat exchanger, a variable relating to the temperature of the liquefied natural gas, the composition of the refrigerant entering the separator of step (d), the pressure in the shell of the main heat exchanger, the pressure in the separator of step (d) and the level of the liquid in the separator of step (d), and wherein the set of variables to be optimized includes the production of liquefied product.

2. Process according to claim 1, characterized in that the set of controlled variables further includes the first mid point temperature difference.

3. Process according to claim 1 or 2, characterized in that the set of controlled variables further includes the second mid point temperature difference.

4. Process according to any one of the claims 1-3, characterized in that the set of controlled variables

further includes the temperature of the gas being liquefied in the first tube side at the midpoint.

5. Process according to any one of the claims 1-4, characterized in that the variable relating to the temperature of the liquefied natural gas is the temperature of the liquefied natural gas removed from the main heat exchanger.

6. Process according to any one of the claims 1-4, further comprising reducing the pressure of the liquefied stream to get the liquefied product which is passed to storage and an off-gas, characterized in that the variable relating to the temperature of the liquefied natural gas is the amount of off-gas.

7. Process according to any one of the claims 1-6, characterized in that adjusting the amount of refrigerant comprises venting gaseous refrigerant.

8. Process according to any one of the claims 1-6, characterized in that adjusting the amount of refrigerant comprises draining liquid refrigerant.

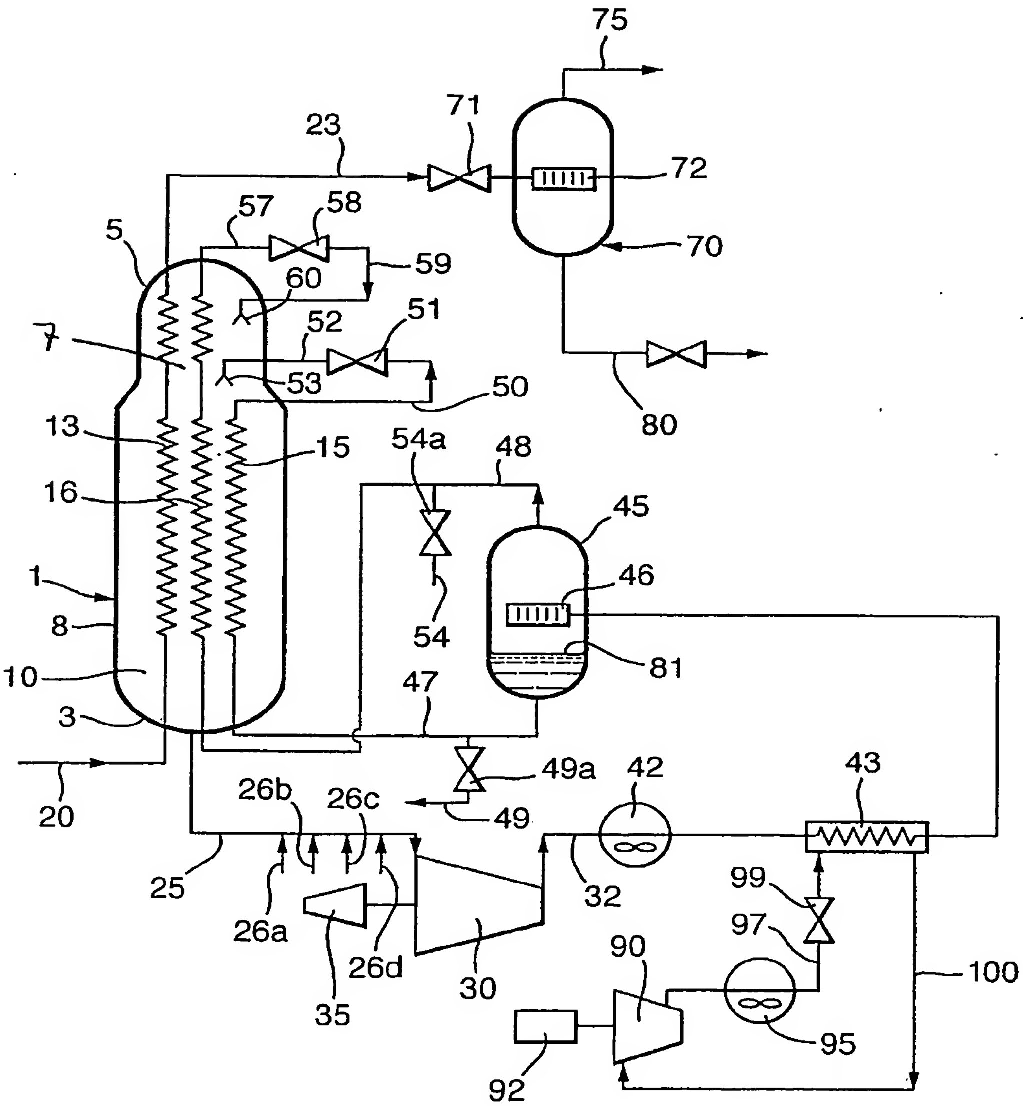
9. Process according to any one of the claims 1-8, wherein the refrigerant includes nitrogen and propane, characterized in that the set of variables to be optimized further includes the nitrogen content of the refrigerant and the propane content of the refrigerant, wherein the nitrogen content is minimized and the propane content is maximized.

10. Process according to any one of the claims 1-8, characterized in that the set of controlled variables further includes the power required to drive the refrigerant compressor(s).

11. Process according to any one of the claims 1-10, characterized in that the manipulated variable capacity of the refrigerant compressor is the speed of the refrigerant compressor, the angle of the inlet guide vane of the refrigerant compressor, or both.

12. Process according to any one of the claims 1-10, wherein partly condensing the high-pressure refrigerant is done in at least one heat exchanger by means of indirect heat exchange with auxiliary refrigerant evaporating at a suitable pressure, and wherein evaporated auxiliary refrigerant is compressed in at least one auxiliary refrigerant compressor and condensed by heat exchange with an external coolant, characterized in that the set of manipulated variables further includes the capacity of the auxiliary refrigerant compressor(s), and in that the set of controlled variables further includes the power required to drive the auxiliary refrigerant compressor(s).

13. Process according to any one of the claims 1-10, characterized in that the manipulated variable capacity of the auxiliary refrigerant compressor is the speed of the auxiliary refrigerant compressor, the angle of the inlet guide vane of the auxiliary refrigerant compressor, or both.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INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP2004/050055

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 F25J1/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 F25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 99/31448 A (DOLBY JONATHAN REYNOLDS ;HODGES DEREK WILLIAM (AU); GROOTJANS HEND) 24 June 1999 (1999-06-24) cited in the application the whole document ---	1-13
Y	US 4 809 154 A (NEWTON CHARLES L) 28 February 1989 (1989-02-28) the whole document ---	1-13
A	EP 0 529 307 A (AIR PROD & CHEM) 3 March 1993 (1993-03-03) page 8, line 20-39 ---	1,7,8

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 April 2004	11/06/2004

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Göritz, D

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 791 160 A (BROCHU PHILIP ALBERT ET AL) 11 August 1998 (1998-08-11) column 8, line 26-58 column 9, line 59 -column 10, line 34; figures 1,3,5	1,5, 10-13
A	DATABASE WPI Section Ch, Week 198933 Derwent Publications Ltd., London, GB; Class H01, AN 1989-240286 XP002245106 -& SU 1 458 663 A (GURIN VALENTIN F; SINITSYN ANATOLIJ (SU); PULIN VALERIJ N (SU)), 15 February 1989 (1989-02-15) abstract; figure	1,6,9
A	US 3 742 721 A (BOURGUET J ET AL) 3 July 1973 (1973-07-03) column 1, line 50 -column 2, line 9; figures	1,9
A	WO 01/81845 A (ELION WIVEKA JACOBA ;JONES KEITH ANTHONY (NL); MCLACHLAN GREGORY J) 1 November 2001 (2001-11-01) abstract	1,5

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP2004/050055

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP2004/050055

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PATENT COOPERATION TREATY

From the
INTERNATIONAL SEARCHING AUTHORITY

To:

see form PCT/ISA/220

PCT

WRITTEN OPINION OF THE INTERNATIONAL SEARCHING AUTHORITY
(PCT Rule 43*bis*.1)

Date of mailing (*day/month/year*) see form PCT/ISA/210 (second sheet)	
Applicant's or agent's file reference see form PCT/ISA/220	**FOR FURTHER ACTION** See paragraph 2 below

International application No.	International filing date (*day/month/year*)	Priority date (*day/month/year*)
PCT/EP2004/050055	30.01.2004	31.01.2003

International Patent Classification (IPC) or both national classification and IPC
F25J1/02

Applicant
SHELL INTERNATIONALE RESEARCH MAATSCHAPPIJ B.V.

1. This opinion contains indications relating to the following items:

- ☒ Box No. I Basis of the opinion
- ☒ Box No. II Priority
- ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
- ☐ Box No. IV Lack of unity of invention
- ☒ Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
- ☐ Box No. VI Certain documents cited
- ☐ Box No. VII Certain defects in the international application
- ☐ Box No. VIII Certain observations on the international application

2. **FURTHER ACTION**

If a demand for international preliminary examination is made, this opinion will usually be considered to be a written opinion of the International Preliminary Examining Authority ("IPEA"). However, this does not apply where the applicant chooses an Authority other than this one to be the IPEA and the chosen IPEA has notifed the International Bureau under Rule 66.1*bis*(b) that written opinions of this International Searching Authority will not be so considered.

If this opinion is, as provided above, considered to be a written opinion of the IPEA, the applicant is invited to submit to the IPEA a written reply together, where appropriate, with amendments, before the expiration of three months from the date of mailing of Form PCT/ISA/220 or before the expiration of 22 months from the priority date, whichever expires later.

For further options, see Form PCT/ISA/220.

3. For further details, see notes to Form PCT/ISA/220.

Name and mailing address of the ISA:	Authorized Officer
European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Göritz, D Telephone No. +49 89 2399-7934

Box No. I Basis of the opinion

1. With regard to the **language**, this opinion has been established on the basis of the international application in the language in which it was field, unless otherwise indicated under this item.

   ☐ This opinion has been established on the basis of a translation from the original language into the following language , which is the language of a translation furnished for the purposes of international search (under Rules 12.3 and 23.1(b)).

2. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application and necessary to the claimed invention, this opinion has been established on the basis of:

   a. type of material:

      ☐ a sequence listing

      ☐ table(s) related to the sequence listing

   b. format of material:

      ☐ in written format

      ☐ in computer readable form

   c. time of filing/furnishing:

      ☐ contained in the international application as filed.

      ☐ filed together with the international application in computer readable form.

      ☐ furnished subsequently to this Authority for the purposes of search.

3. ☐ In addition, in the case that more than one version or copy of a sequence listing and/or table relating thereto has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

4. Additional comments:

Re Item V

Reasoned statement with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. **Prior Art**

The following documents (D1-D6) are referred to in this communication; the numbering will be adhered to in the rest of the procedure:

D1: WO 99 31448 A

D2: US-A-4 809 154

D3: EP-A-0 529 307

D4: US-A-5 791 160

D5: SU-A-1 458 663 & DATABASE WPI Week 33 Derwent Pub. Ltd., London, GB; AN 1989- 240286 XP002245106

D6: US-A-3 742 721

2. **Independent Claims**

The subject-matter of independent **claim 1** is new, but does not involve an inventive step (Articles 33(1) and (3) PCT).

2.1 Document D1, which is considered to represent relevant state of the art, discloses (see figure 1) the features of the liquefaction process according to the preamble of claim 1 and further discloses the feature of controlling the process using an advanced process controller based on a model predictive control to determine simultaneous control actions for a set of manipulated variables in order to optimize the production of liquefied product whilst controlling a set of controlled variables wherein the set of manipulated variables includes the mass flow rates of the heavy and light refrigerant fractions, the capacity of the refrigerant compressor and the mass flow rate of the methane-rich feed and wherein the set of controlled variables includes the temperature differences at the warm end of the main heat exchanger and the temperature of the liquefied product

2.2 from which the subject-matter of claim 1 differs in that the set of manipulated variables further includes the amount of refrigerant components make-up and of refrigerant removed and that the set of controlled variables further includes the composition of the refrigerant entering the separator, the pressure in the shell of the main heat exchanger and the pressure and the liquid level in the separator.

Box No. II Priority

1. ☐ The following document has not been furnished:

   ☐ copy of the earlier application whose priority has been claimed (Rule 43*bis*.1 and 66.7(a)).

   ☐ translation of the earlier application whose priority has been claimed (Rule 43*bis*.1 and 66.7(b)).

   Consequently it has not been possible to consider the validity of the priority claim. This opinion has nevertheless been established on the assumption that the relevant date is the claimed priority date.

2. ☒ This opinion has been established as if no priority had been claimed due to the fact that the priority claim has been found invalid (Rules 43*bis*.1 and 64.1). Thus for the purposes of this opinion, the international filing date indicated above is considered to be the relevant date.

3. Additional observations, if necessary:

Box No. V Reasoned statement under Rule 43*bis*.1(a)(i) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-13
	No:	Claims	
Inventive step (IS)	Yes:	Claims	
	No:	Claims	1-13
Industrial applicability (IA)	Yes:	Claims	1-13
	No:	Claims	

2. Citations and explanations

see separate sheet

2.3 It is well known from the art, that the control of the composition of the mixed refrigerant provides an improved controlling of the liquefaction process, see Document D2 and also D3 to D5 (reference is made to the citation of the International Search Report). In the process of D2 the amount of refrigerant components make-up and of refrigerant removed are manipulated by the control system by controlling the composition of the refrigerant entering the separator, the pressure in the shell of the main heat exchanger and the pressure and the liquid level in the separator. Consequently, it is not apparent that these particular features of manipulated respectively controlled variables for the control of the composition of the mixed refrigerant in the process of D1 leads to any particular unexpected technical effects.

2.4 Therefore, it would be obvious to the person skilled in the art, to apply these features with corresponding effect to the process according to document D2, thus arriving at claimed subject-matter.

3. Dependent Claims

Dependent **claims 2 to 13** do not appear to contain any additional features which, in combination with the features of any claim to which they refer, meet the requirements of Article 33(1) PCT. The additional features of said claims are partly known from above cited document D1 (claims 2 to 6 and 11 to 13) or form part of the normal consideration of the man skilled in the art with respect to the available prior art D2 to D6 (claims 7 to 10). See also the corresponding passages cited in the search report.

Consequently, the subject-matter of said claims appears to lack inventive step (Article 33(3) PCT).

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY REPORT ON PATENTABILITY

(Chapter II of the Patent Cooperation Treaty)

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference TS 1330 PCT	**FOR FURTHER ACTION**	See Form PCT/IPEA/416
International application No. PCT/EP2004/050055	International filing date *(day/month/year)* 30.01.2004	Priority date *(day/month/year)* 31.01.2003
International Patent Classification (IPC) or national classification and IPC F25J1/02		
Applicant SHELL INTERNATIONALE RESEARCH MAATSCHAPPIJ B.V.		

1. This report is the international preliminary examination report, established by this International Preliminary Examining Authority under Article 35 and transmitted to the applicant according to Article 36.
2. This REPORT consists of a total of 5 sheets, including this cover sheet.
3. This report is also accompanied by ANNEXES, comprising:
   a. ☐ *sent to the applicant and to the International Bureau)* a total of sheets, as follows:
      - ☐ sheets of the description, claims and/or drawings which have been amended and are the basis of this report and/or sheets containing rectifications authorized by this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions).
      - ☐ sheets which supersede earlier sheets, but which this Authority considers contain an amendment that goes beyond the disclosure in the international application as filed, as indicated in item 4 of Box No. I and the Supplemental Box.

   b. ☐ *(sent to the International Bureau only)* a total of (indicate type and number of electronic carrier(s)) , containing a sequence listing and/or tables related thereto, in computer readable form only, as indicated in the Supplemental Box Relating to Sequence Listing (see Section 802 of the Administrative Instructions).

4. This report contains indications relating to the following items:

   - ☒ Box No. I Basis of the opinion
   - ☐ Box No. II Priority
   - ☐ Box No. III Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
   - ☐ Box No. IV Lack of unity of invention
   - ☒ Box No. V Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
   - ☐ Box No. VI Certain documents cited
   - ☐ Box No. VII Certain defects in the international application
   - ☐ Box No. VIII Certain observations on the international application

Date of submission of the demand 27.10.2004	Date of completion of this report 28.04.2005
Name and mailing address of the international preliminary examining authority: European Patent Office D-80298 Munich Tel. +49 89 2399 - 0 Tx: 523656 epmu d Fax: +49 89 2399 - 4465	Authorized Officer Göritz, D Telephone No. +49 89 2399-7934

Box No. I Basis of the report

1. With regard to the **language**, this report is based on the international application in the language in which it was filed, unless otherwise indicated under this item.

   ☐ This report is based on translations from the original language into the following language , which is the language of a translation furnished for the purposes of:
   - ☐ international search (under Rules 12.3 and 23.1(b))
   - ☐ publication of the international application (under Rule 12.4)
   - ☐ international preliminary examination (under Rules 55.2 and/or 55.3)

2. With regard to the **elements*** of the international application, this report is based on *(replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report)*:

Description, Pages

1-15 as originally filed

Claims, Numbers

1-13 as originally filed

Drawings, Sheets

1/1 as originally filed

☐ a sequence listing and/or any related table(s) - see Supplemental Box Relating to Sequence Listing

3. ☐ The amendments have resulted in the cancellation of:
   - ☐ the description, pages
   - ☐ the claims, Nos.
   - ☐ the drawings, sheets/figs
   - ☐ the sequence listing *(specify)*:
   - ☐ any table(s) related to sequence listing *(specify)*:

4. ☐ This report has been established as if (some of) the amendments annexed to this report and listed below had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).
   - ☐ the description, pages
   - ☐ the claims, Nos.
   - ☐ the drawings, sheets/figs
   - ☐ the sequence listing *(specify)*:
   - ☐ any table(s) related to sequence listing *(specify)*:

* *If item 4 applies, some or all of these sheets may be marked "superseded."*

Box No. V Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Yes:	Claims	1-13
	No:	Claims	-
Inventive step (IS)	Yes:	Claims	1-13
	No:	Claims	-
Industrial applicability (IA)	Yes:	Claims	1-13
	No:	Claims	-

2. Citations and explanations (Rule 70.7):

see separate sheet

Re Item V

1. **Prior Art**

The following documents (D1-D5) are referred to in this communication; the numbering will be adhered to in the rest of the procedure:

D1: WO 99 31448 A
D2: US-A-4 809 154
D3: EP-A-0 529 307
D4: US-A-5 791 160
D5: SU-A-1 458 663 & DATABASE WPI Week 33 Derwent Pub. Ltd., London, GB; AN 1989- 240286 XP002245106

2. **Independent Claims**

The subject-matter of independent **claim 1** is new and involves an inventive step (Articles 33(1) and (3) PCT).

2.1 Document D1, which is considered to represent relevant state of the art, discloses (see figure 1) the features of the liquefaction process according to the preamble of claim 1 and further discloses the feature of controlling the process using an advanced process controller based on a model predictive control to determine simultaneous control actions for a set of manipulated variables in order to optimize the production of liquefied product whilst controlling a set of controlled variables wherein the set of manipulated variables includes the mass flow rates of the heavy and light refrigerant fractions, the capacity of the refrigerant compressor and the mass flow rate of the methane-rich feed and wherein the set of controlled variables includes the temperature differences at the warm end of the main heat exchanger and the temperature of the liquefied product

2.2 from which the subject-matter of claim 1 differs in

(I) that the set of manipulated variables further includes the amount of refrigerant components make-up and of refrigerant removed,

(ii) that the set of controlled variables further includes the composition of the refrigerant entering the separator, the pressure in the shell of the main heat exchanger and the pressure and the liquid level in the separator and

(iii) that the control actions for the set of manipulated variables are simultaneously

determined.

2.3 The objective problem solved by these distinguishing features of claim 1 is to obtain improved optimisation of the production of liquefied product.

2.4 In the process of D2 the amount of refrigerant components make-up and of refrigerant removed are manipulated by the control system by controlling the composition of the refrigerant entering the separator (see col. 8, l. 12-17), the pressure in the shell of the main heat exchanger ("compressor suction pressure", see col. 7, l. 6-29, and table 1, point 50, "M" and "N") and the pressure (deductible from "compressor suction pressure" and "compression ratio") and the liquid level (see col. 8, l. 12-17) in the separator. At least some of these features are also known from similar processes disclosed by D3 to D5 (see also the corresponding passages cited in the International Search Report). Although it is also known from this prior art, that these features provide an improved controlling of the liquefaction process, the prior art lacks disclosing the combination of these features with the determination of the control actions for the set of manipulated variables in a simultaneous manner. In particular, it would not appear to be obvious to use the sequential determination of the control actions in D2 in the process of D1. Consequently, the subject-matter of **claim 1** can therefore be considered as involving an inventive step (Article 33(3) PCT).

3. Dependent Claims

Claims 2-13 are dependent on claim 1 and as such also meets the requirements of the PCT with respect to novelty and inventive step (Article 33(2) and (3) PCT).